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TERAHERTZ (THZ) RADAR: A SOLUTION FOR DEGRADED VISIBILITY ENVIRONMENTS (DVE)

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13. ABSTRACT (Maximum 200 Words)

Testing results are presented in this report of the imaging capabilities of an experimental radar system operating at Terahertz (THz) frequencies. Preliminary measurements are encouraging and validate the system's relatively high resolution and ability to tune the frequency to compensate for environmental conditions, allowing for actionable images in Degraded Visibility Environments (DVE).

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I. INTRODUCTION

An accurate view of the physical world is frequently vital. For example, rotary wing aircraft pilots must have knowledge of the terrain in order to safely fly their aircraft. Therefore, systems capable of generating images of the environment of sufficient quality to facilitate the decision process are necessary. The product of such a system is illustrated in Figure 1. Radar systems are often employed to provide an accurate image; however, the performance of radar systems in a given environment is dependent upon the frequencies at which they operate. Since objects appear different when using different observation systems, development of new approaches for viewing the world would offer new information that could prove critical in situations where currently standard techniques are inadequate. One such situation occurs in Degraded Visual Environments (DVE), such as the brownout illustrated in Figure 2. In this type of situation, the observation system must be capable of overcoming the visual obscurants and providing high-resolution images of the environment in order to facilitate the decision process.

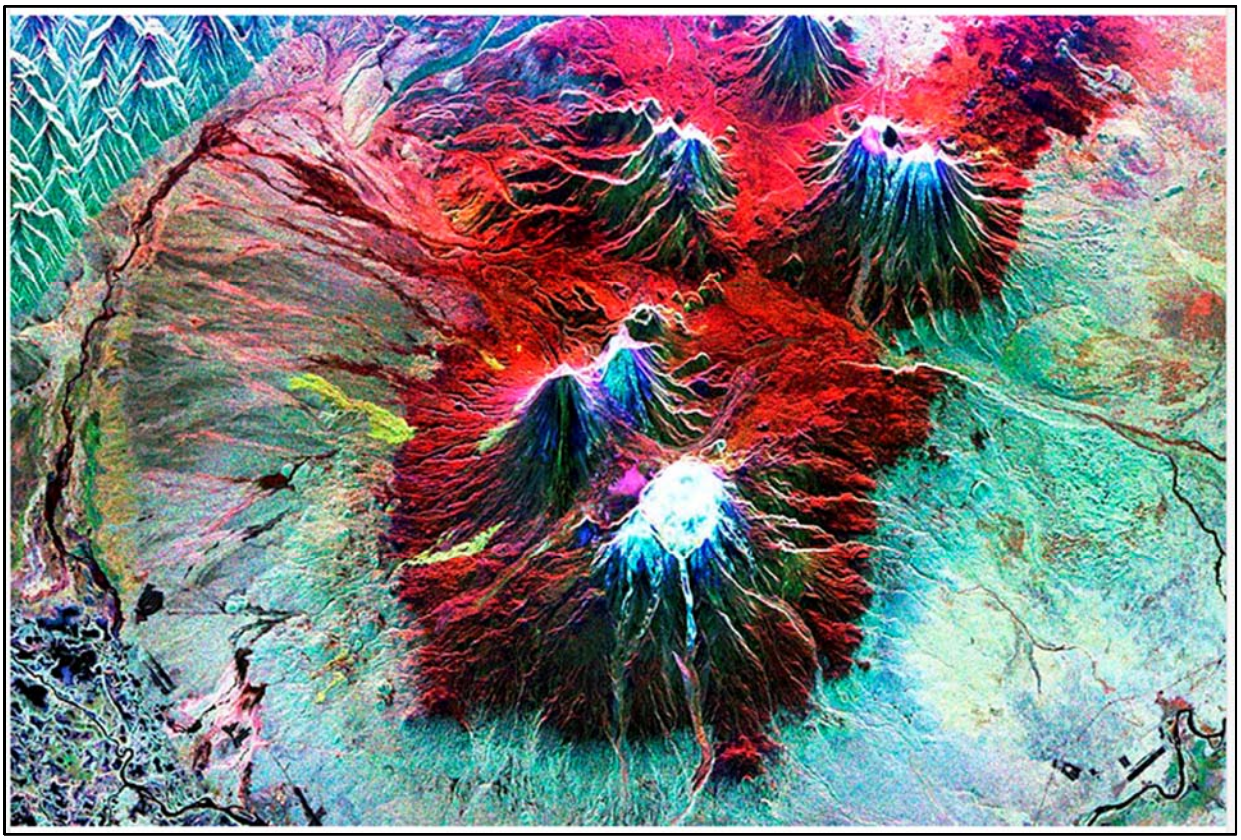


Figure 1. Terrain Map Generated From Radar Data

Figure 2. Brownout

II. CURRENT APPROACHES

Currently, lidar, a radar-like system that utilizes frequencies in the visual spectrum and millimeter wave (MMW) radar are the most common solutions to DVE. However, while lidar can produce useful images at reasonable Size, Weight, and Power (SWaP), lidar's relatively lower obscurant penetration produces problems in several types of DVE. On the other hand, MMW radars must have a high SWaP in order to produce similar quality images, resulting in degradation of image quality in order to meet the limits of the platform on which the radar will be used.

III. CONCEPT

To overcome the limitations of lidar and MMW solutions, a Terahertz (THz) radar was developed as a potential solution for DVE imaging. Although the THz band is not thoroughly explored, it offers several advantages for an imaging solution. To test the potential of a THz imager, the Active Covert Terahertz Imager (ACTI), as shown in Figure 3, was designed and built by Mustang Technology, now a subsidiary of L3, Inc. Operating at 300 to 330 gigahertz (GHz), the ACTI is among the world's highest frequency radars (lidar excluded). By operating at higher frequencies relative to MMWs, the ACTI can employ higher gain antennas at reasonable SWaP, thereby producing tighter beams and finer resolution. The higher frequencies also offer easy utilization of higher bandwidth components, allowing for finer range resolution. The increase in frequency and corresponding decrease in wavelength also decreases the minimum size required for an object to be detectable. In addition, while the frequency is

high for a true radar, the frequency is sufficiently low for the radiation to penetrate obscurants, such as dust storms.

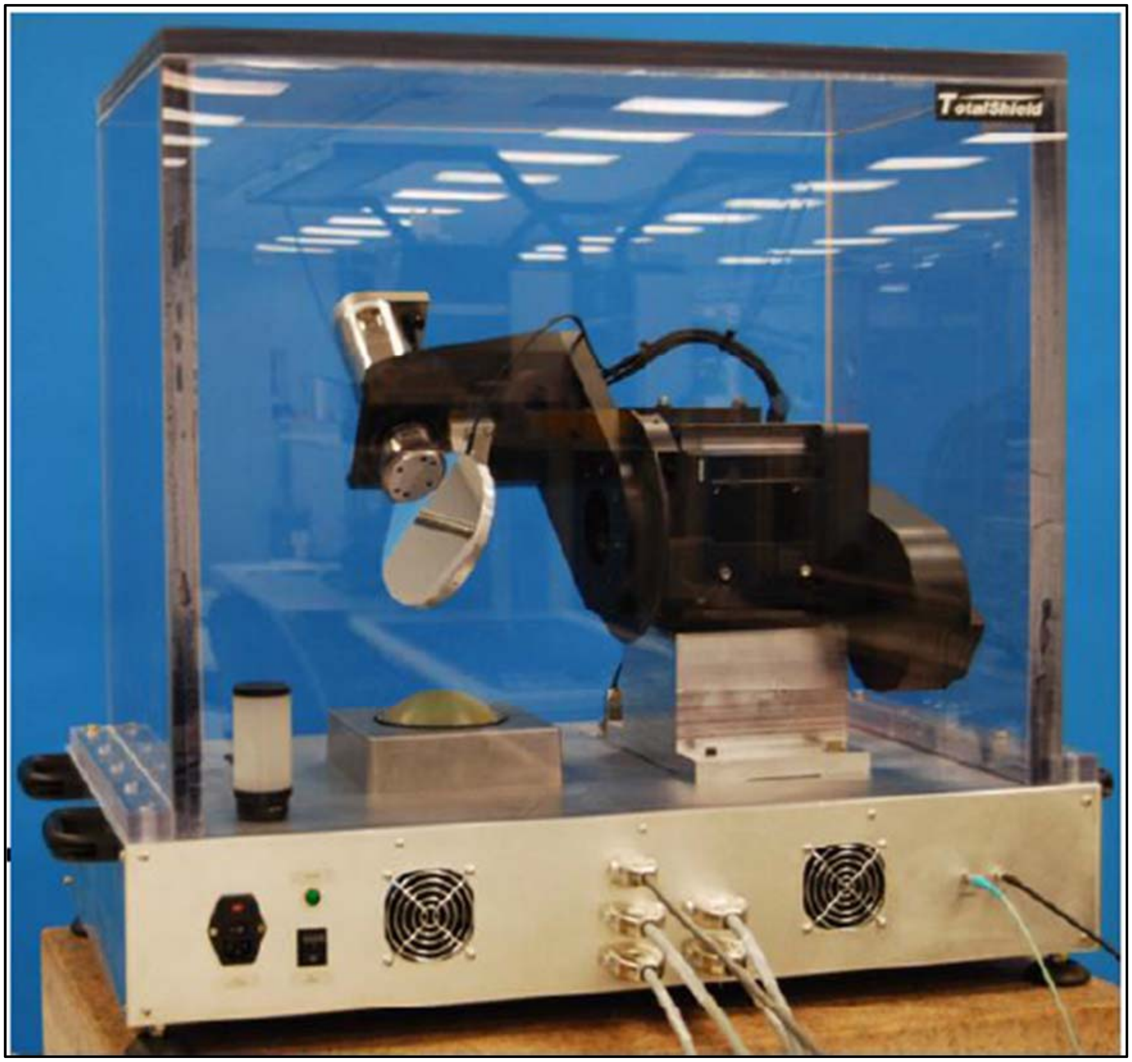


Figure 3. ACTI

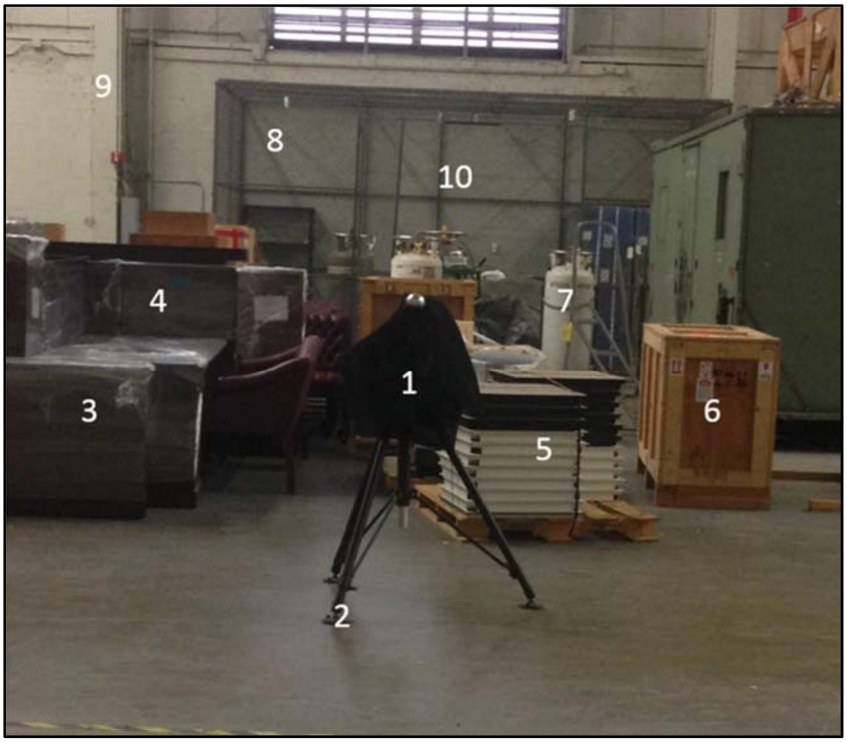
The ACTI is a Frequency-Modulated Continuous-Wave Radar (FMCW). The beam is mechanically steered by a rotating mirror, thus providing real beam imaging and an imaging time in single-digit seconds. The beam width is 0.5 degrees (°), and the field of view is 45° horizontal by 30° vertical. With its output power of 5 milliwatts (mW) and antenna gain of 50 decibels relative to isotropic (dBi), the ACTI is safe for imaging humans even at a range as close as 1 meter (m).

IV. EXPERIMENTATION

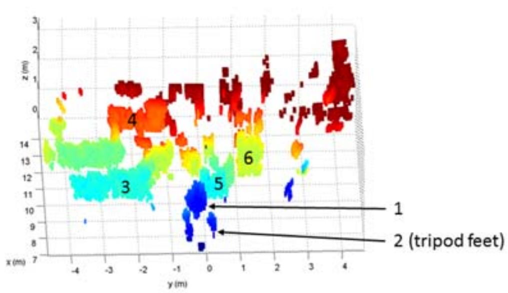
A. Imaging Capabilities

To test the capabilities of the ACTI, a scene of varying objects was imaged. Figure 4 shows that the image produced by the ACTI matches well with the camera image of the scene.

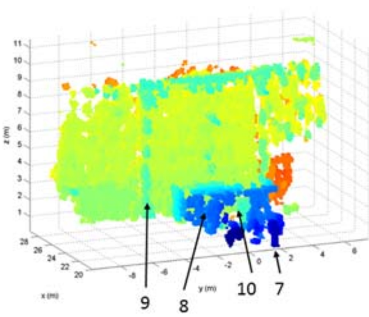
While the precise nature of the objects is not revealed by the radar image; the sizes, shapes, and locations of the objects are relatively accurate; and the image provides a great deal of information about the scene.



(a) Camera Image



(b) ACTI Image, Close Range

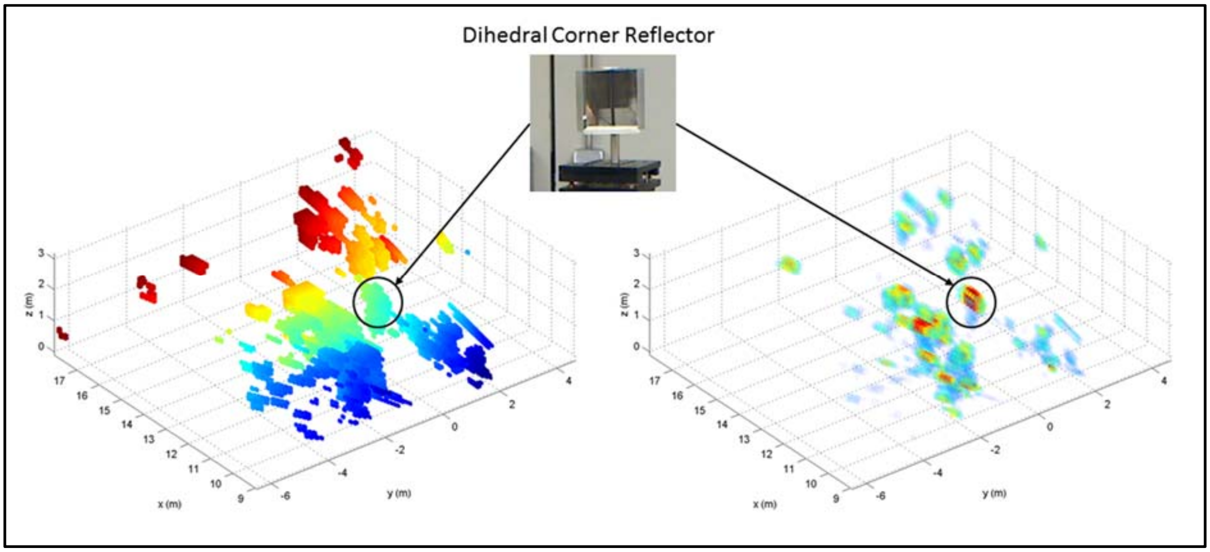


(c) ACTI Image, Mid-Range

Figure 4. Comparison of Images Produced by Camera and ACTI

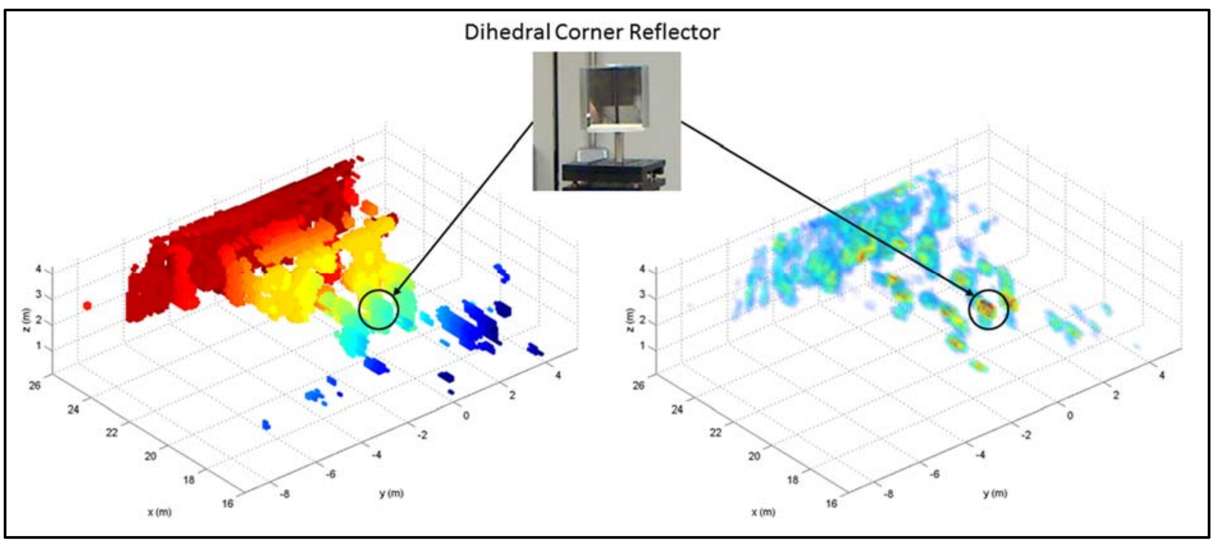
The ability to locate strong reflectors hidden among other objects was tested next. A scene similar to Figure 4 was used but with several key changes. First, the Radar Cross Section (RCS) sphere on the tripod was replaced with a dihedral corner reflector. Second, the tripod was moved to a position in the midst of other objects. Figures 5 and 6 show the resulting images from the two tests. When return-intensity-based display filters are applied, the corner reflector is readily apparent, demonstrating that the ACTI could be used to locate more precisely reflectors whose approximate position is known. However, it was observed that the reflector

produces a return of such strong intensity that the return causes Fourier transform rolloff (smoothing of the image into adjacent range bins), causing the reflector to appear significantly larger than it actually is. While this feature is useful for locating the reflector, it provides a slight degree of uncertainty as to the precise location of the reflector.



(a) Range *(b) Intensity*

Figure 5. Close Range Locating of Strong Reflector Plots With Color



(a) Range *(b) Intensity*

Figure 6. Mid-Range Locating of Strong Reflector Plots With Color

Tests were then conducted to examine the resolution of the ACTI. The first test demonstrated that a human can be imaged and is easily identifiable when the limbs are slightly spread and the body is facing the ACTI, as shown in Figure 7. A later test, illustrated in Figure 8, showed that bodies with legs together and arms extended parallel to the ground oriented to present the side of the body to the ACTI are much more difficult to identify as

human. Figure 9 shows, however, that bodies with one side presented to the ACTI can be easily identified as human if the limbs are not held to the sides. Furthermore, the imaging resolution is sufficient to identify the difference in the ranges for each of the subject's arms. Finally, Figure 10 shows that the resolution is sufficient even to identify a subject giving a thumbs up sign.

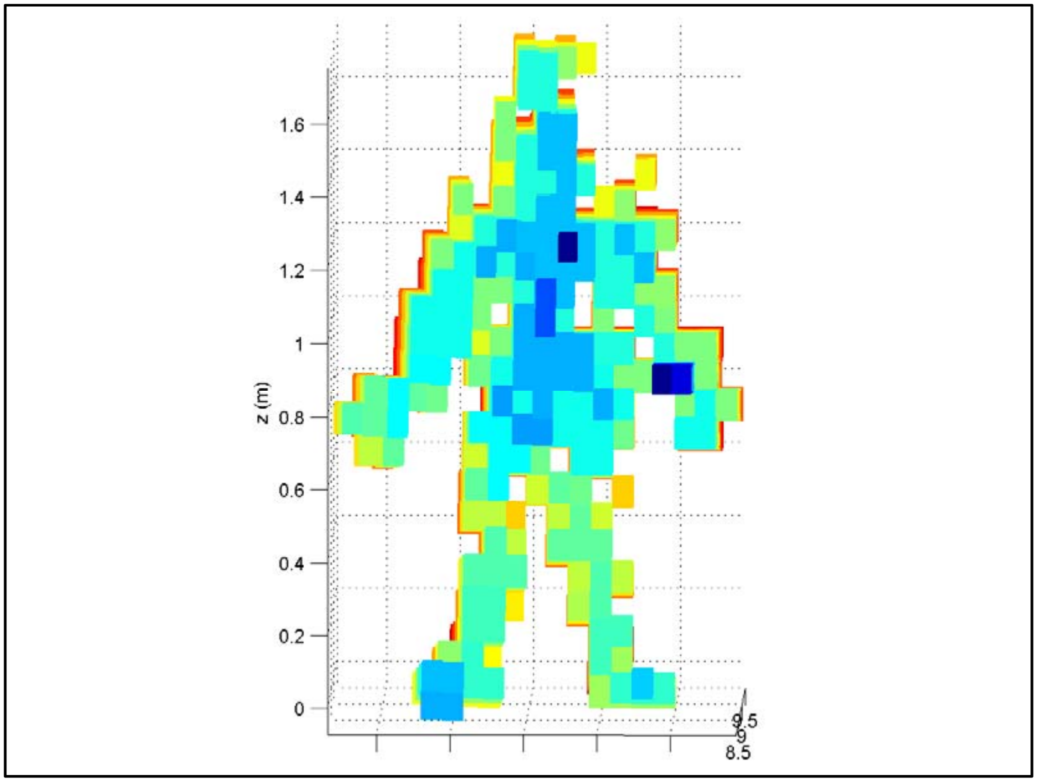
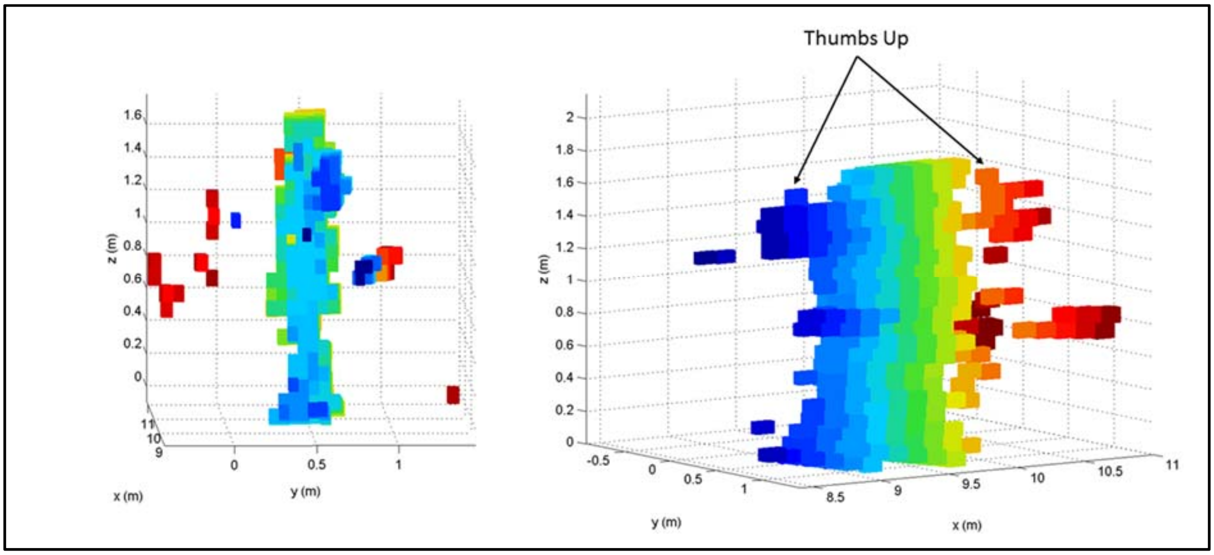
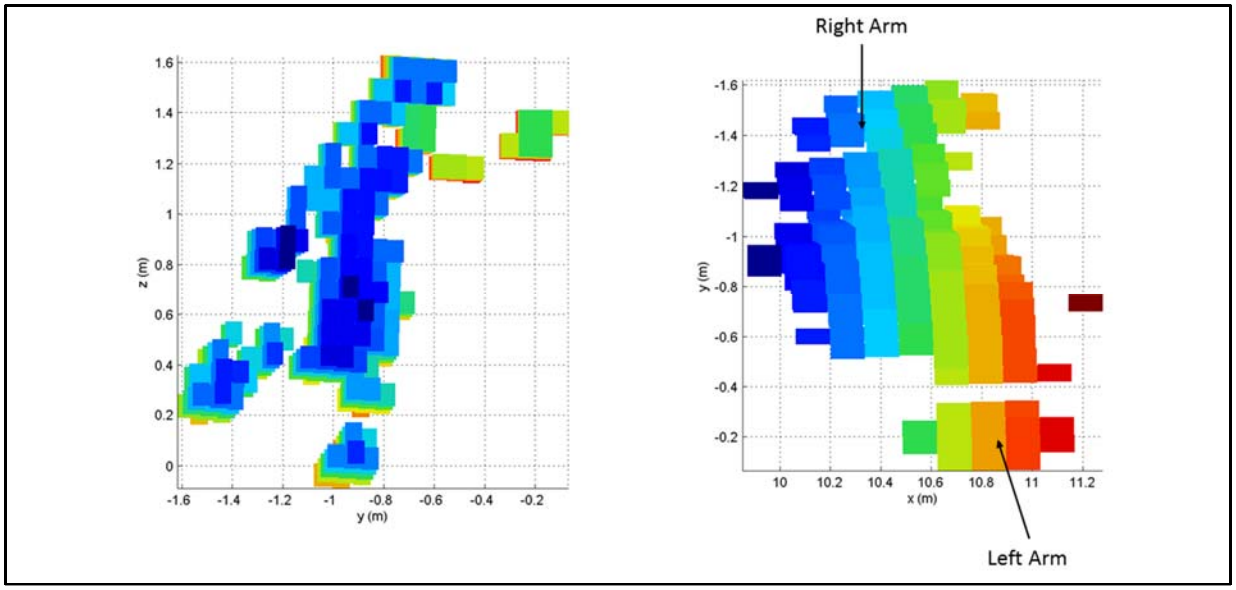


Figure 7. Human Facing ACTI



(a) Front View *(b) Angled Side View*

Figure 8. Human With Side to ACTI



(a) Front View *(b) Top View*

Figure 9. Human in Running Pose With Side to ACTI

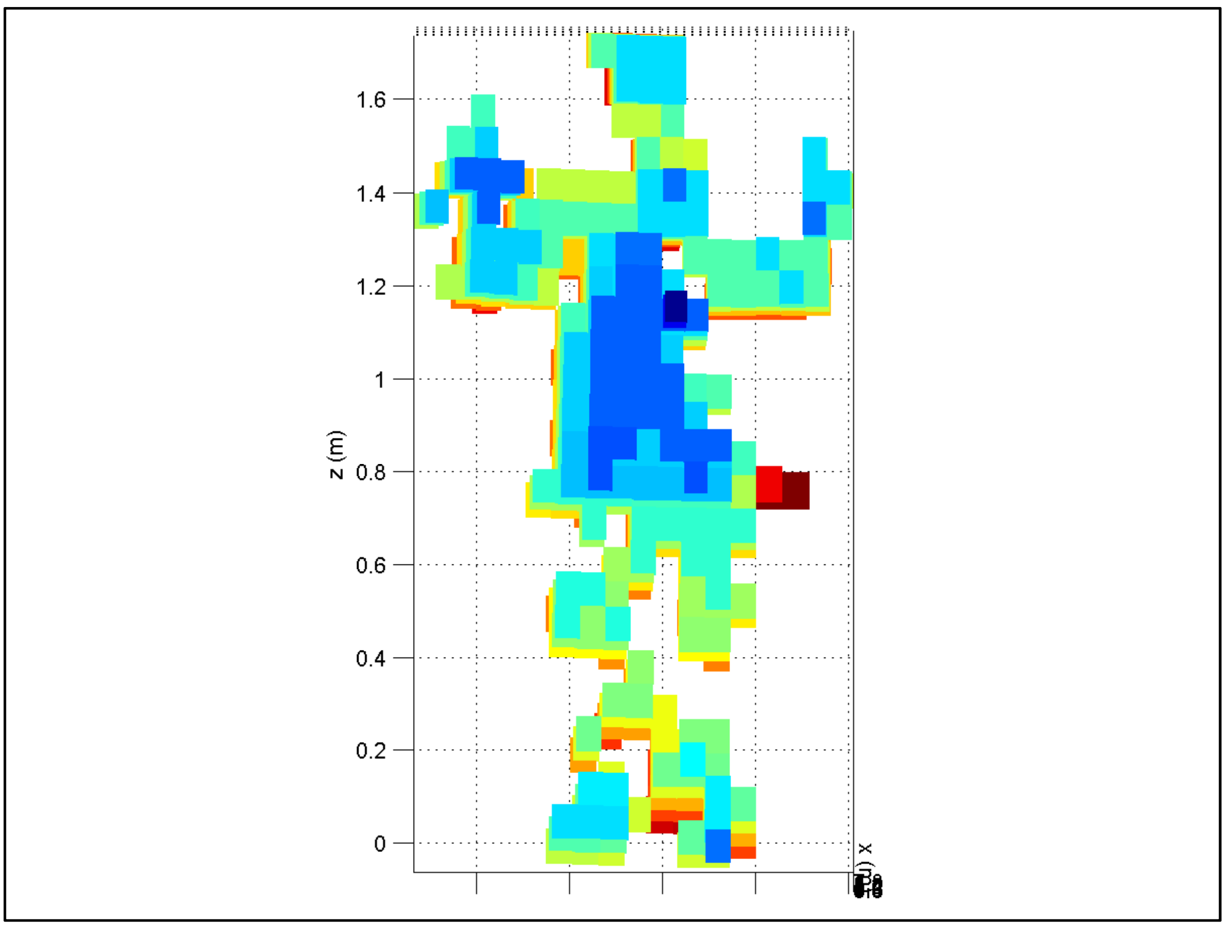


Figure 10. Human Giving Thumbs Up While Facing ACTI

Next, a scene was imaged with a partially obstructing object, a chain link fence. Despite the small diameter of the wire, the fence is clearly visible, as seen in Figure 11. However, even though the fence is readily detectable, the ACTI can perceive objects beyond the fence without issue.

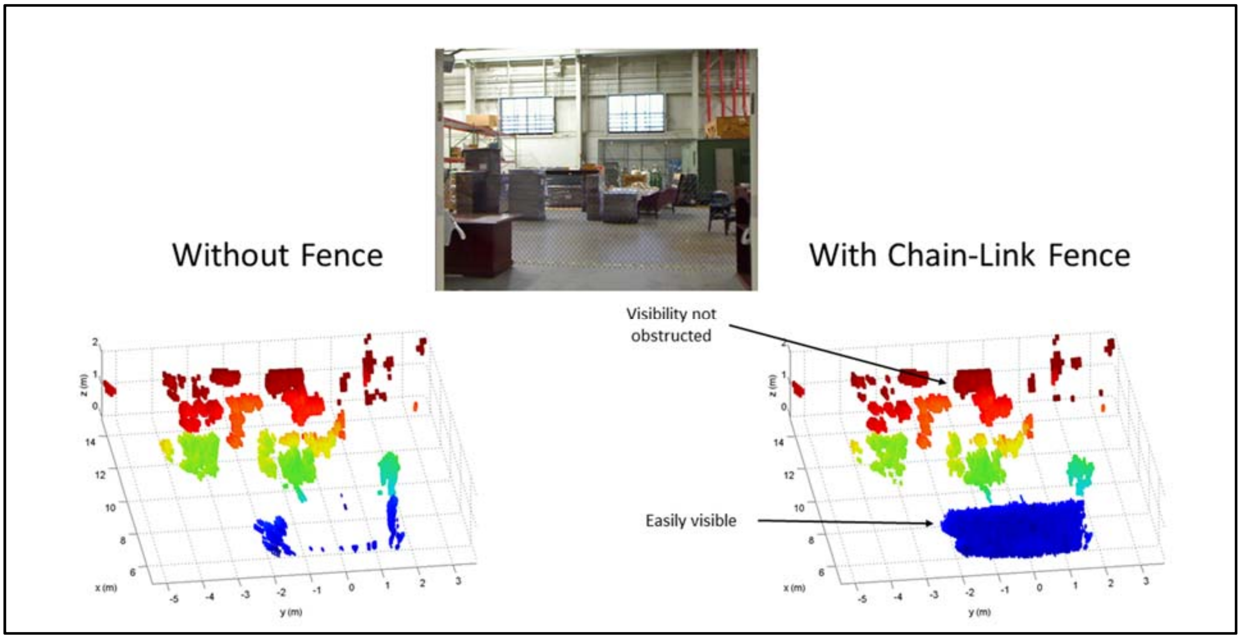


Figure 11. Effect of Chain Link Fence

B. Frequency Variation

The attenuation, or decrease in signal strength, that occurs as an electromagnetic wave passes through the atmosphere is dependent on the frequency of the wave. Figure 12 shows that the amount of attenuation that the ACTI signal experiences varies significantly with frequency and dew point (a measure of humidity). The maximum attenuation for ACTI frequencies for a given dew point occurs at approximately 325 GHz. This is known as a water line due to the increase resulting from absorption by gaseous water. As the attenuation increases, returns decrease in strength. Atmospheric attenuation is more significant at longer ranges as the signal must pass through a greater distance of air.

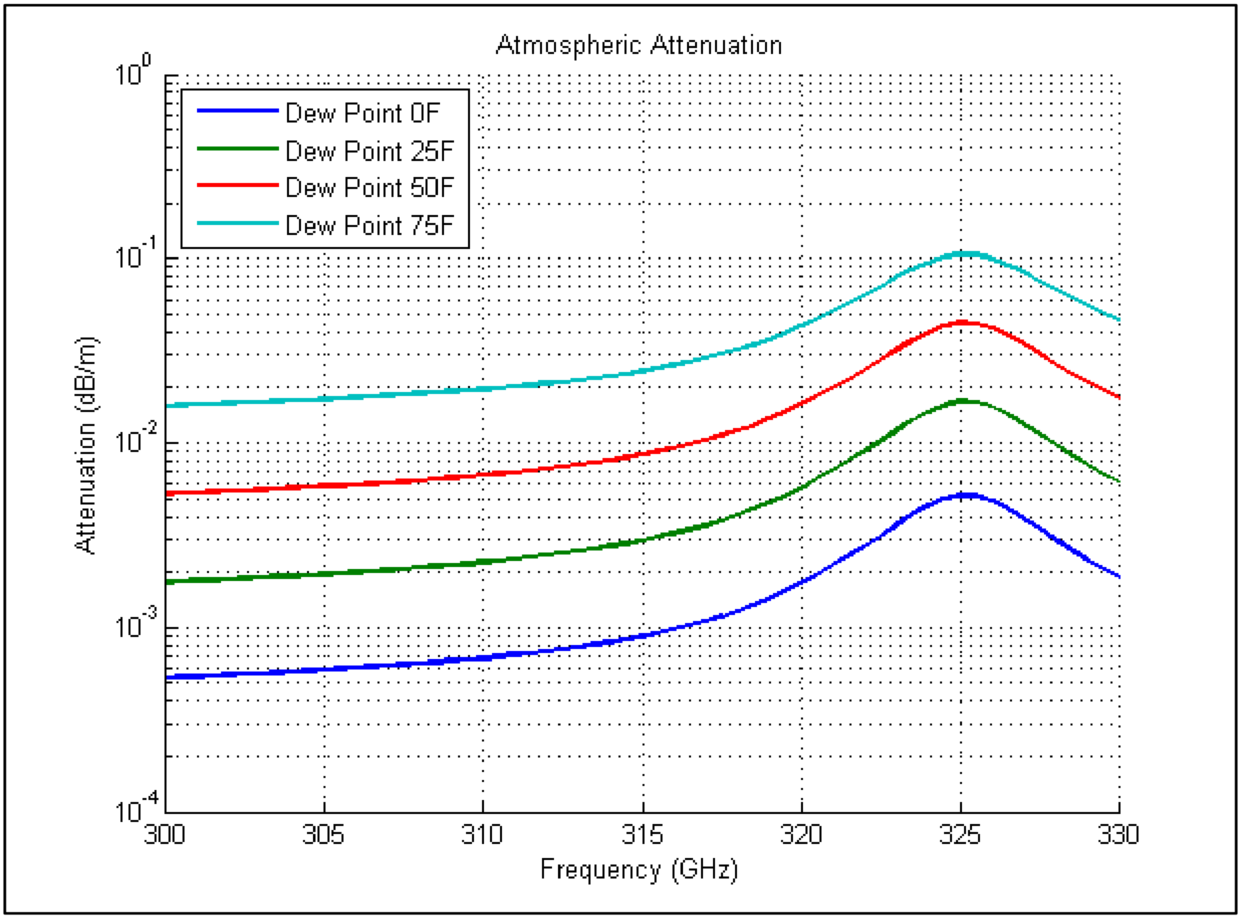


Figure 12. Attenuation Versus Frequency and Dew Point

Several experiments were performed to observe the behavior of the ACTI when changing frequency. First, Figure 13 appears to demonstrate that changing the frequency from 315 to 325 GHz produces only a minor impact at a range of approximately 12 m. Second, Figure 14 shows that frequency makes a significant impact on the strength of returns at approximately 25 m. The difference in the severity of the effect due to changing the attenuation is consistent with changing the range to the target. Furthermore, the attenuation is predicted to increase as the frequency increases from 315 to 325 GHz, and then the attenuation is predicted to decrease as the frequency continues to increase from 325 to 328 GHz. This increase followed by decrease is noted in the results. Third, Figure 15 shows that dew point has a significant impact on the strength of returns, which was expected since the amount of attenuation resulting from atmospheric water is proportional to the amount of water in the atmosphere. These three experiments demonstrate that the ACTI performs qualitatively as predicted.

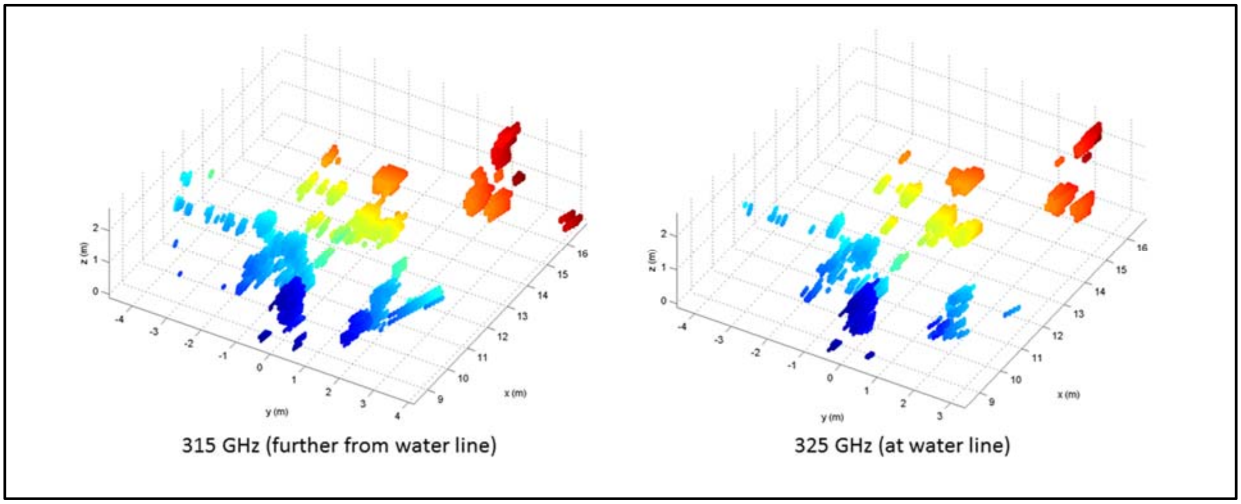


Figure 13. Effect of Frequency at Close Range

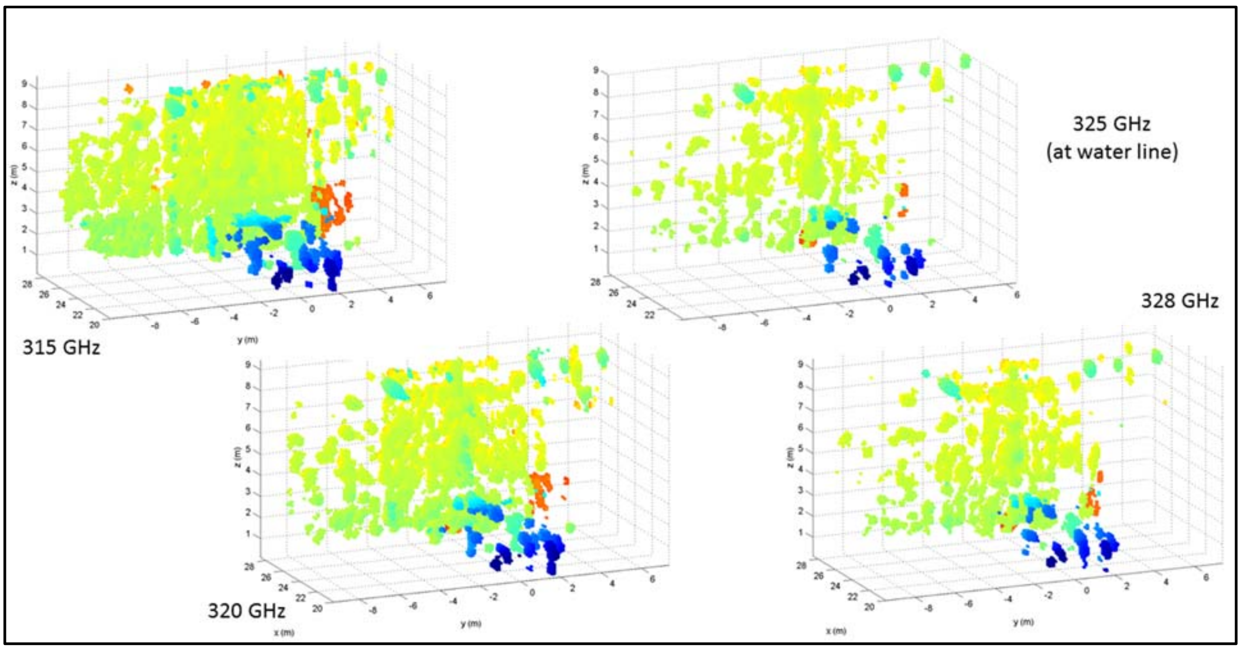


Figure 14. Effect of Frequency at Mid-Range

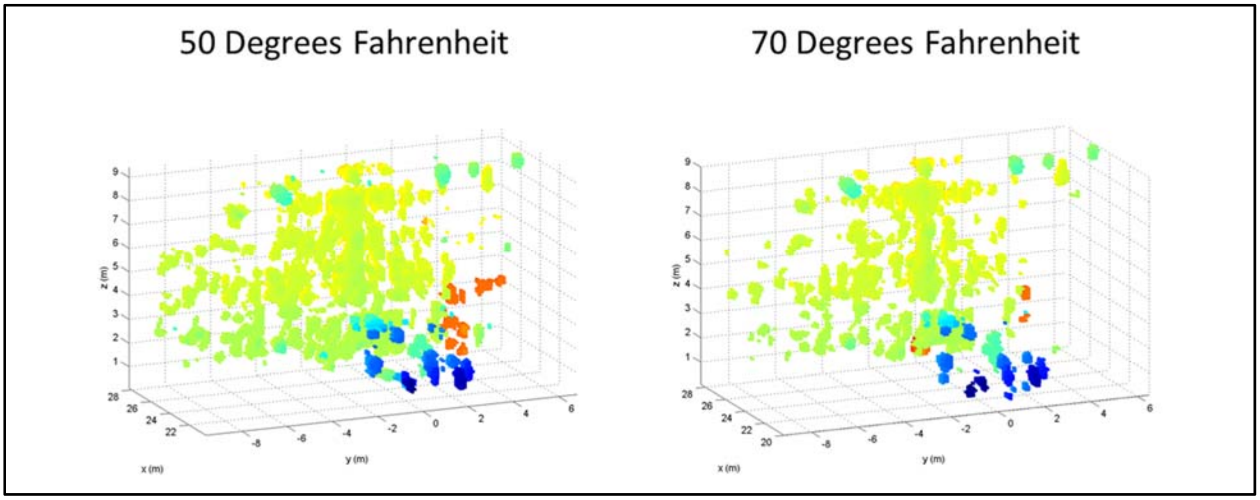


Figure 15. Effect of Dew Point at Mid-Range

The radar range equation is $R_{max} = \sqrt[4]{\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 kTBL(S/N)}}$, where R_{max} is the maximum range of the radar, P_t is the transmit power, G is the antenna gain, λ is the wavelength, σ is the RCS of the target, k is Boltzmann's Constant, T is the absolute temperature, B is the noise bandwidth, L is the total loss, and S/N is the minimum Signal-to-Noise Ratio (SNR). Based on this equation and assuming that atmospheric attenuation is the only contribution to total loss, Figures 16 and 17 plot the theoretical maximum limits at which the ACTI could perceive a target with an SNR of at least 15 decibels (dB) as functions of frequency and dew point. In Figure 16, the target has an RCS of 0 decibels per square meter (dBsm), and the target for Figure 17 is a dihedral corner reflector with an RCS of 28.7 dBsm at 315 GHz. Figure 18 illustrates the theoretical SNR as a function of frequency and dew point for this dihedral corner reflector placed at a range of 50 m. However, there are additional hardware losses unaccounted for in these calculations.

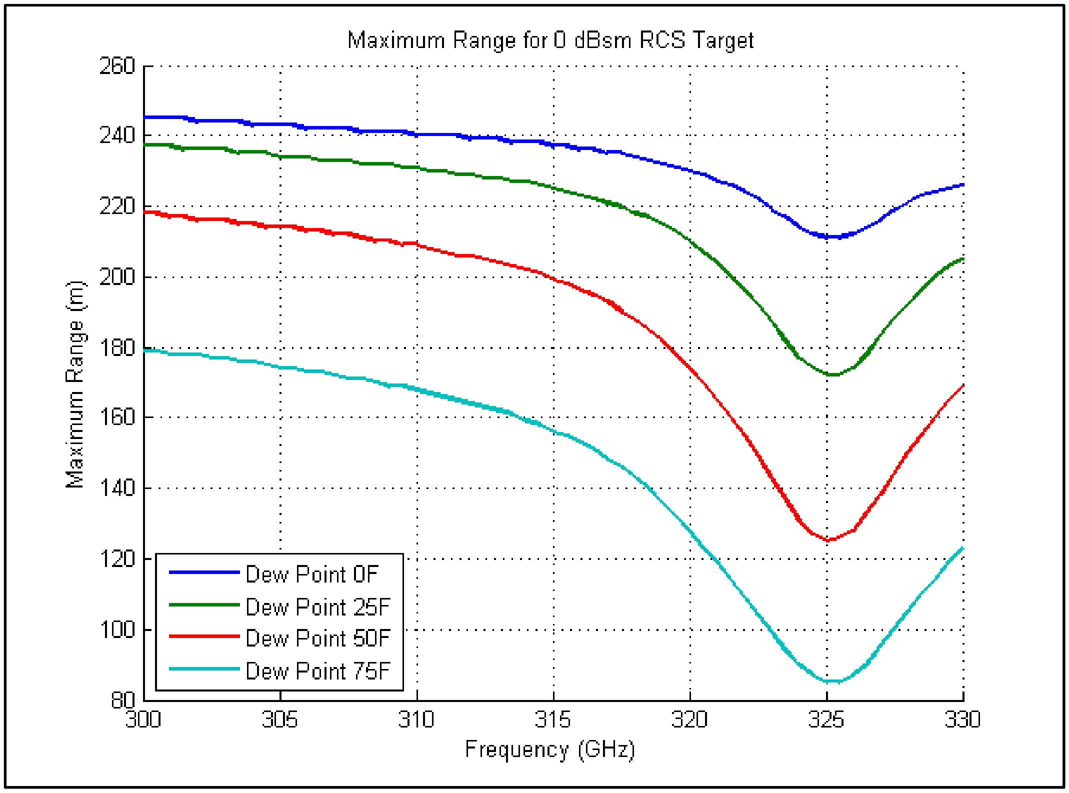


Figure 16. ACTI Maximum Range for Detection of 0 dBsm RCS Target

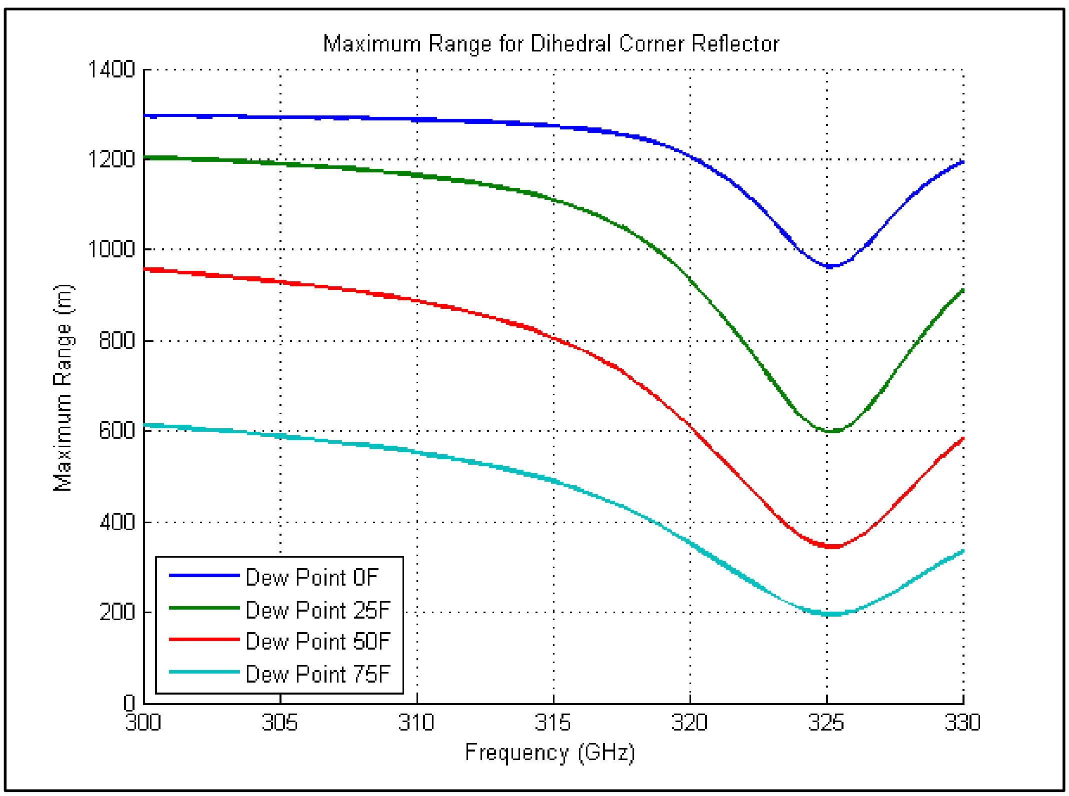


Figure 17. ACTI Maximum Range for Detection of Dihedral Corner Reflector

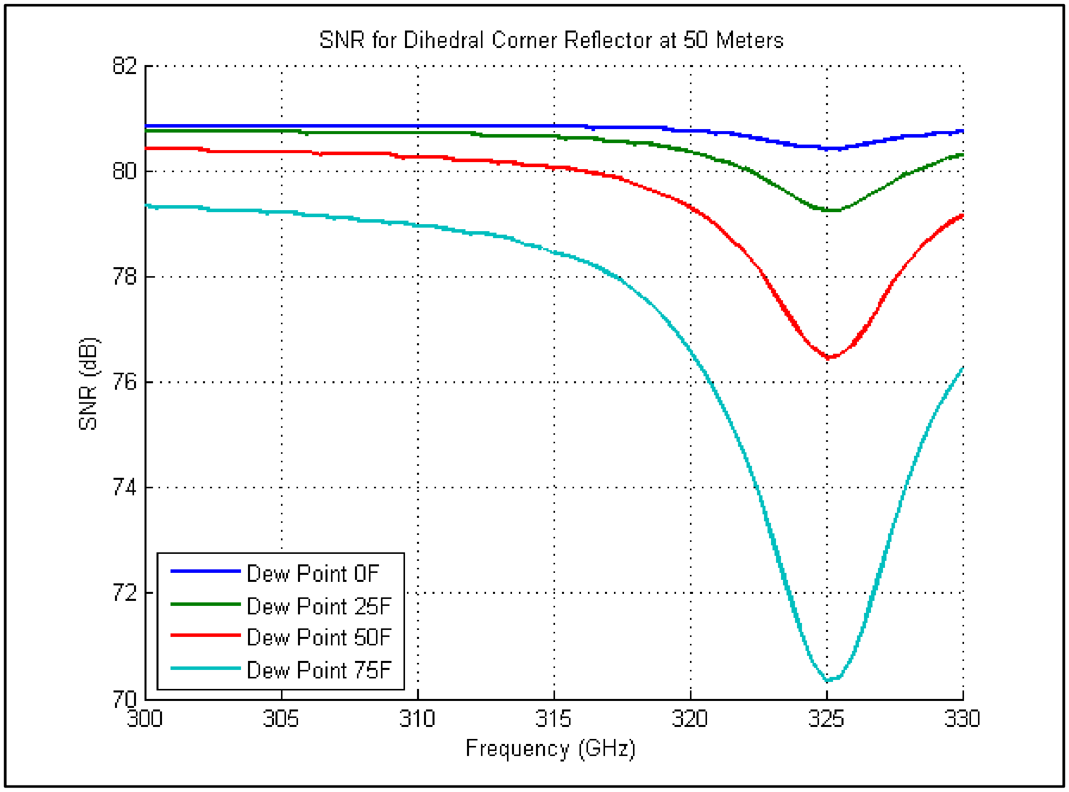


Figure 18. ACTI SNR for Dihedral Corner Reflector at 50 m

To test the radar's signal with respect to frequency, a dihedral corner reflector (RCS of 28.7 dBsm at 315 GHz) was imaged at 8 m on a day with a dew point of approximately 75 °F. The maximum strengths of returns from that reflector, rounded down to the nearest dB, were recorded and plotted as a function of frequency in Figure 19. The noise level was approximated and is graphed in Figure 20, and the SNR is graphed in Figure 21. The variation in return strength is likely due in large part to variation in output power resulting from mode mismatch, which manifests as inefficiencies in the coupling of energy inside frequency multipliers. The variation in noise is likely a result of Townes noise from the heterodyne receiver, as evidenced by the larger noise levels nearer to the ACTI at frequencies with high noise levels. The SNR change with frequency is a result of the combined effects of mode mismatch, Townes noise, and atmospheric attenuation.

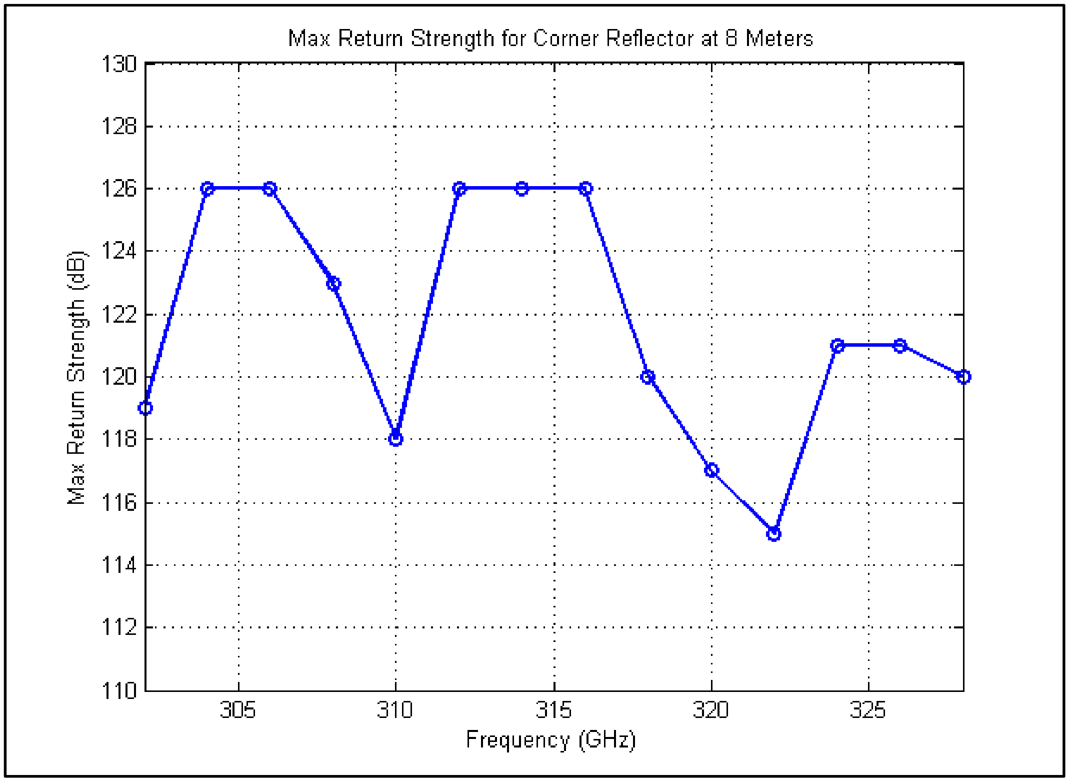


Figure 19. Maximum Return Strength for Dihedral Corner Reflector at 8 m

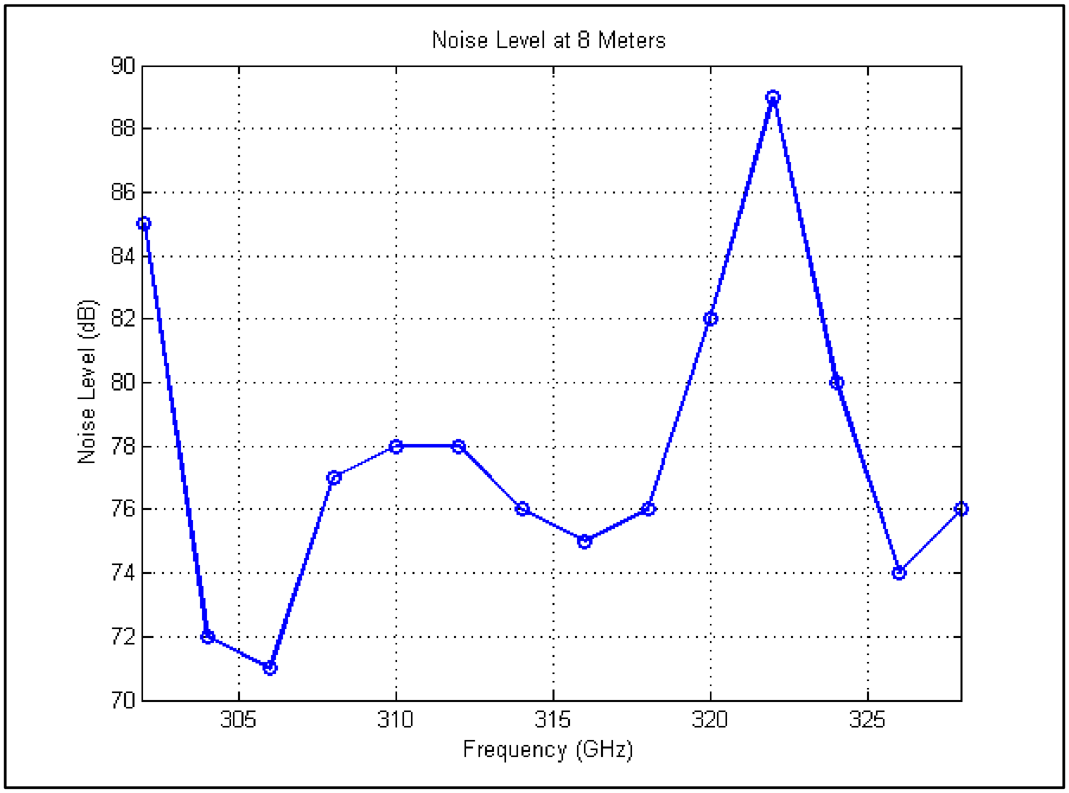


Figure 20. Noise Level at 8 m

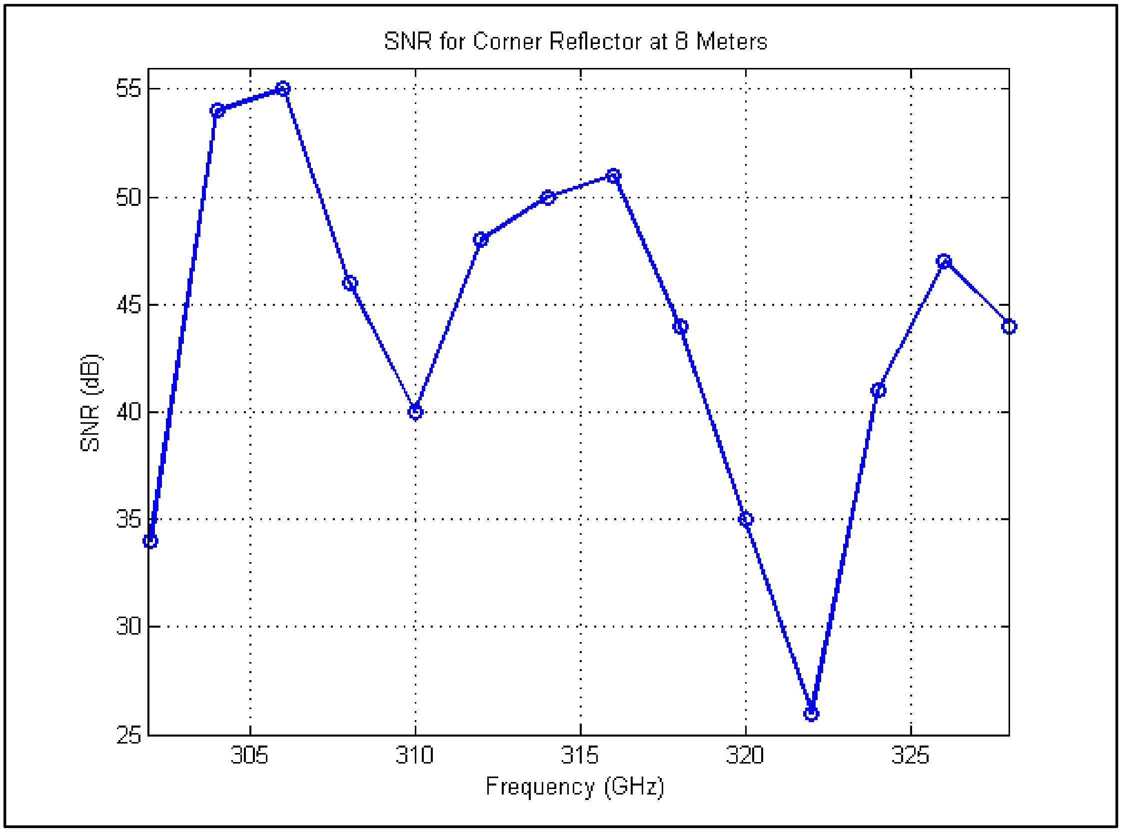


Figure 21. SNR for Dihedral Corner Reflector at 8 m

V. RESULTS

The ACTI has proven that it can provide actionable quality images of objects of varying sizes and shapes. The ACTI has further demonstrated a high resolution for its SWaP, including the ability to detect rather small features of the scene that it is imaging, such as a thumbs up sign. In addition, the chain link fence, despite the small diameter of the fence wire, was readily visible using the ACTI but did not impair the ACTI's capability to image objects behind the fence, as might have occurred with other radar systems.

The ACTI demonstrated its ability to utilize or compensate for environmental conditions. At close range, the ACTI has sufficient output power to overcome minor detrimental conditions. For longer ranges, the frequency can be adjusted to decrease the attenuation in humid environments to provide higher quality images, or the frequency can be adjusted to increase attenuation if the signal needs to be hidden from detection. These capabilities can be applied to other environmental factors as well. For example, dust in the air causes attenuation that is dependent on frequency. The attenuation can be measured, and the ACTI's frequency can be adjusted to allow improved vision through dust storms and brownout or to utilize these same conditions to aid in masking the signal.

VI. CONCLUSIONS

A THz imager, such as the ACTI, can be used to produce actionable images. A frequency-tunable THz imager can be used to utilize or overcome environmental conditions.

VII. FUTURE EFFORTS

Additional tests should be conducted to verify the ability of the ACTI to observe scenes during adverse environmental conditions such as fog and dust storms. The next phase of the ACTI should incorporate the ability to vary the bandwidth based on the desired resolution. The next phase should further reduce the SWaP as well.

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

°	degree
ACTI	Active Covert Terahertz Imager
dB	decibel
dBi	decibels relative to isotropic
dBsm	decibel per square meter
DVE	Degraded Visual Environments
F	Fahrenheit
FMCW	Frequency-Modulated Continuous-Wave Radar
GHz	Gigahertz
m	meter
MMW	millimeter wave
mW	milliwatts
RCS	Radar Cross Section
S/N	Signal to Noise
SNR	Signal-to-Noise Ratio
SWaP	Size, Weight, and Power
THz	Terahertz